Design of Transport Casks with Depleted Uranium Gamma Shield and Advanced Safety

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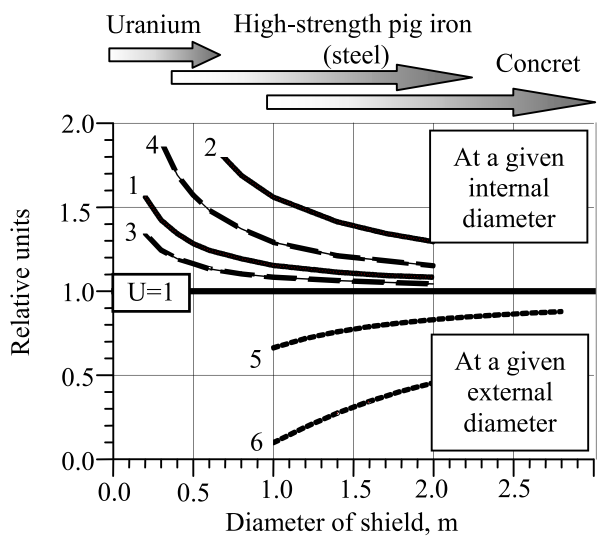
Abstract - *The report is dedicated to a problem of creation of a new generation of dual-purpose transport packing complete sets (TPCS)[1] with advanced safety. These sets are intended for transportation and storage of spent nuclear fuel assemblies (SNFA)[2] of VVER reactors and spent spark elements (SSE)[3] of plutonium production uranium-graphite ADE type reactors. Meeting of all IAEA safety requirements (TS-R-1) and advanced resistance of TPCS at accidents and terrorist attacks has been achieved due to the use of depleted uranium (DU)[4] for the design of dual-purpose TPCS. It is supposed to use metallic DU simultaneously both as an effective gamma shield and structural material. Use of metallic DU for a design of dual-purpose TPCS allows to achieve maximum capacity of container, to meet all TS-R-1 safety requirements and provide the advanced stability at accidents and terrorist acts.*

I. INTRODUCTION

In Russia and abroad there is an objective necessity for a new generation of TPCS for transportation, storage and disposal of accumulated spent nuclear fuel (SNF)[5] reserves and radioactive waste. The containers currently used in Russia and other countries are intended only for transportation. Storage or disposal of SNF cannot be implemented. The problem can be resolved by creation of the multi-purpose universal containers intended, both for transportation and storage, and for SNF and radioactive waste disposal. The basic requirements to such containers are:

- Conformity to the TS-R-1 requirements;
- Maximum safety at operating conditions, accidents and also at probable acts of terrorism;
- Maximum capacity per mass and size unit;
- Minimum overall dimensions per capacity unit adapted to all kinds of transports;
- The specific cost (cost per 1 t of uranium transferred) compared to the specific cost of metal-concrete designs.

Based on the listed requirements the profound study of shielding materials was carried out. The relative mass and dimensional parameters of different shields are shown in fig. 1



1 - External diameter of pig iron shield,
2 - External diameter of concrete shield,
3 - weight of pig iron shield,
4 - weight of concrete shield,
5 - Capacity of the pig iron cask,
6 - Capacity of the concrete cask

Fig.1. The mass and dimensional parameters

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[1] TPCS – **T**ransport **P**acking **C**omplete **S**et
[2] SNFA – **S**pent **N**uclear **F**uel **A**ssembly
[3] SSE – **S**pent **S**park **E**lement
[4] DU – **D**epleted **U**ranium
[5] SNF – **S**pent **N**uclear **F**uel

The combination of electronic and nuclear density of uranium and low-alloyed uranium makes these materials the best one for use as a gamma radiation shield for designs of universal containers. On the other hand, the materials of universal containers should provide a maximum design safety not only at operating conditions and accidents, but also at probable acts of terrorism. Therefore the materials used must have a high strength property.

The comparative parameters of as-cast biological shield materials are shown in table I.

TABLE I. Parameters of biological shield materials

Parameter	Material		
	High-strength pig iron	Steel 1020	Uranium alloy
Density, g/cm^3	6.8 – 7.0	7.3 – 7.5	18.3 – 18.5
Ultimate strength σ_B	400 MPa	420 MPa	>800 MPa
Yield strength σ_{02}	380 MPa	240 MPa	600 MPa
Percentage elongation δ	< 5 %	18 %	6.0 %
Impact strength	10 J/cm^2	18 J/cm^2	50 J/cm^2
Fracture	Brittle fracture at -40^{o}C	Brittle at -20^{o}C	Tough fracture at -40^{o}C

The mechanical characteristics of uranium alloys in the best way meet the requirements for structural materials of biological shield.

The concept of a dual-purpose universal TPCS with advanced safety was proposed for SNF transportation and storage. This concept combines both the ideas of DU effective utilization and DU use as structural and shielding material.

Meeting of all TS-R-1 safety requirements as well as advanced TPCS stability at accidents and terrorist attacks are provided due to metallic DU utilization. For Russian Agency for Atomic Energy (ROSATOM) accumulating huge quantity of depleted uranium (processed waste of the uranium productions) the development of a new generation TPCS on a base of metallic DU is the most rational and perspective way. It allows solving a problem of the accumulated DU stockpiles utilization rather effectively because now they do not find any application and thus create an ecological hazard to an environment.

The similar technical policy concerning a new generation of TPCS for SNF is being performed now in USA with regard to not smaller DU stockpiles [1]. These stockpiles were created as a result of production of fissile materials in frames of military programs. In DOE there is a program, valid up to 2010, on creation of multi-purpose containers on a base of DU for SNF storage, transportation and disposal, because DU provides the most effective gamma shield and maximum safety [2].

II. A NEW GENERATION CONTAINERS ON A BASE OF DEPLETED URANIUM

R&D activities to create new generation dual-purpose TPCS on a base of DU intended for SNF transportation and storage were started by VNIINM[1] and RFNC-VNIIEF[2] at the beginning of the 90-th and are going on till the present time.

As a result of such activities the large amount of computational, theoretical, exploratory and technological investigations were carried out. As a result:

- As-cast uranium alloys, in particular the special uranium alloy BZ-2[3] was developed. The properties of this alloy under different operating conditions of the gamma-shielding unit were investigated. The efficiency of BZ-2 under such conditions within 50 years was demonstrated. The small containers with uranium alloys designed were already used for transportation, storage and management of high-level radioactive materials in an industry, science and medical engineering. The subsequent technological investigations allow us to recommend the uranium alloys designed not only for small shield at transportation and management of high-level radioactive materials but also as a material for multitonn radioactive shield of transport casks;
- New know-how of gamma shield units manufacturing was developed and tested in a production scale. We have applied the process of uranium alloy casting directly into a leakproof ring jacket mould. Further rings were connected by argon-arc welding in the single unit being simultaneously a structural load-bearing element [3]. For prevent an interaction between stainless steel and uranium the especial coating was developed. It protects steel reliably up to temperature of 1400°C;
- The engineering design of a dual-purpose TPCS-117, intended for transportation and storage of VVER-1000

[1] VNIINM - Bochvar Institute of Inorganic Materials
[2] RFNC-VNIIEF – Russian Federal Nuclear Center – All-Russian Research Institute of Experimental Physics
[3] BZ-2 – **B**iological Shield (in Russian – **Z**ashita)

SNFA (capacity equals to 36 SNFA) was developed. In accordance to the requirements of national and international Regulations the computational and theoretical substantiation of safety was made. Besides, the safety of TPCS at accidents and acts of terrorism on NPP[1], storage sites and processing plants was computed;
- The preliminary design of dual-purpose TPCS, intended for transportation and storage of 120 SSE of plutonium production uranium-graphite ADE-type[2] reactors was developed, and the preliminary computational and theoretical investigations of its different safety aspects were carried out.

II.A. Dual-Purpose TPCS-117

The engineering design of dual-purpose TPCS-117 [4] that is intended for temporary storage and transportation of VVER-1000 36 SNFA involves the manufacturing of multitonn radiation uranium shield using the know-how described above.

Mass and overall dimensions of TPCS-117 provide realization of indispensable operations with the container and basket inside NPP, container depot and stationary SNFA depot. They also allow transportation of the container in a horizontal state on special goods-carriage, made pursuant to Russian Standard 02-BM. Besides the TPCS-117 design provides a possibility of transportation by a water transport and enables the local displacement by auto-car transport on special trailers (NPP-port, NPP-railway station).

TPCS consist of: the shielding container 1 - strong cylindrical leakproof shell (vessel) and basket 2, which is set inside of the shielding container and serves for the ordered disposition of the 36 VVER-1000 SNFA.

General view of a TPCS-117 is shown in a fig. 2.

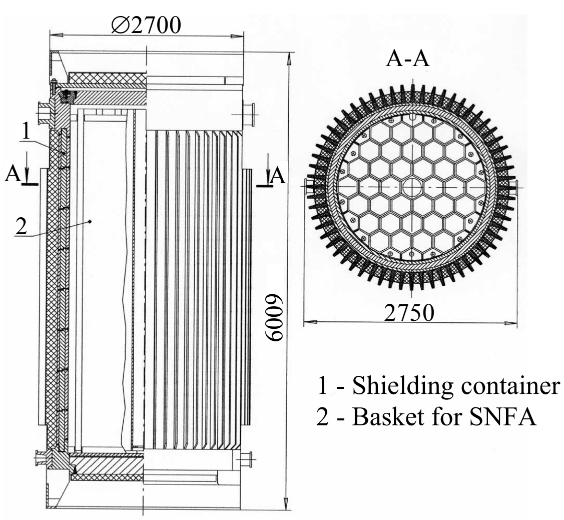

Fig. 2. General view of TPCS-117

Main parameters of TPCS-117 are:
- Capacity - 36 VVER-1000 SNFA,
- Mass of empty TPCS, not more than 102.5 t,
- Mass of loaded TPCS, not more than 144.5 t,
- Effective life, not less than 50 years.

II.A.I. Shielding Container

The shielding container of TPCS-117 consists of body and two pressure sealing covers.

The body of shielding container looks like a multilayer cylindrical sleeve consisting of:
- Internal power shell,
- Lateral uranium gamma-shield,
- External power shell,
- Lateral neutron shield,
- Bottom with the neutron shield and lower shock absorber,
- Heat-output ribs with outside facing (lateral shock absorber),
- Two top lifting eyes for a container lifting,
- Two lower lifting eyes for overturning of container in a horizontal state.

The internal and external power shells are made of a stainless steel 12Cr18Ni10Ti. The thickness of the internal power shell is 40 mm; thickness of the external shell is 30 mm.

The lateral gamma shield is made of BZ-2 alloy on a base of depleted uranium and its thickness is 72 mm.

Internal power shell, lateral uranium gamma shield and external power shell form a three-layer cylindrical shell, which is the basic supporting element of a container design. We named it BBGS[1]. BBGS is collected of 8 ring elements. Leakproof welds weld rings with each other. The bottom is welded to the lower BBGS's face end.

60 longitudinal heat-output ribs having a U-profile and manufactured of a sheet stainless steel 15 mm in thickness are welded on a BBGS outside surface. These ribs act as a lateral shock absorber side by side with a function of the heat-output. 60 facings made of 5-mm sheets of stainless steel have a leakproof weld with heat-output ribs. The fragment of heat-output ribs, outside facings and lateral neutron shield is shown in fig. 3.

The space between ribs and facings is filled with siloxane rubber and forms the lateral neutron shield 140-mm in thickness. Top and bottom neutron shield and shock absorbers are set on an external side of covers.

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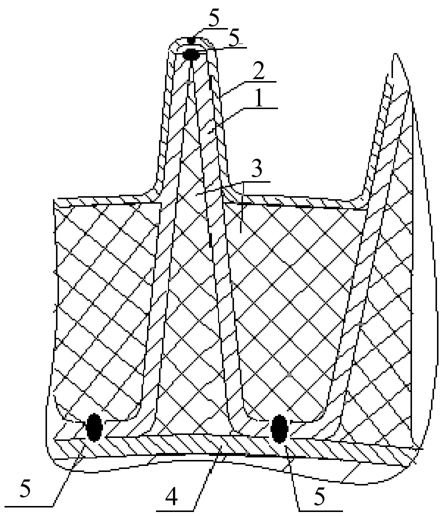
[1] NPP – **N**uclear **P**ower **P**lant

[2] ADE – Type of Russian plutonium production reactors



1 - Heat-output ribs; 2 - Outside facings;
3 - Lateral neutron shield;
4 - External power shell; 5 - Weld

Fig. 3. Fragment of heat-output ribs, outside facings and lateral neutron shield

II.A.II. Basket

The general view of the basket used in TPCS-117 for ordered disposition of 36 VVER-1000 SNFA is shown in a fig. 4.

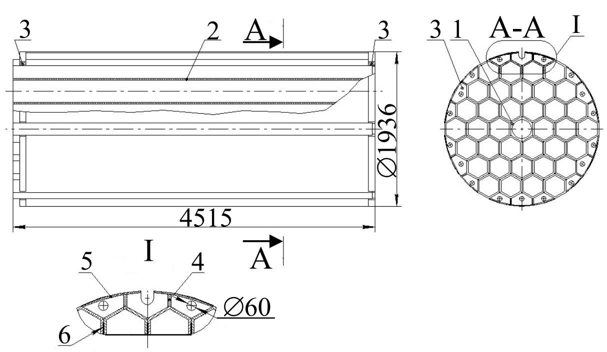


Fig.4. General view of a basket

The basket used in TPCS-117 represents a welded construction consisting of following main elements:
- Central hexahedral tube for its holding during the process of installation into the container, taking out from the container and local displacement outside of the container (position 1 in fig. 4);
- 36 technological hexahedral tubes for the SNFA installation (position 2 in fig. 4);
- 6 lower and 6 upper support segments (position 3 in fig. 4);
- 12 heat-output ribs (position 4 in fig. 4);
- 18 heat-output facings (position 5 in fig. 4).

The structural members of a basket are manufactured of aluminum alloy AMG-6[2], having the low density, high physical, mechanical, thermal and processing properties, and also improved corrosion resistance in aggressive acid-alkaline medium.

The boron plates for neutron absorption (position 6 in fig. 4) were included in a basket structure also.

The large capacity basket designed for TPCS-117 differs by a design simplicity and technology. It has no analogy in domestic and foreign container building.

II.A.III. BBGS’s Technology

BBGS is made as a three-layer (steel – uranium-steel) cylindrical shell made up of 8 elemental rings in a height. Pressure-tight welds on internal and external shells connect rings with each other.

Cycle of ring element manufacturing includes the following operations:
- Manufacturing and preparation of the jacket mould;
- Melting and casting of uranium alloy BZ-2 into the prepared jacket mould;
- Machining of the open face end;
- Leakproof welding of the finished face end (argon-arc welding);
- Machining of the ring element up to the final sizes.

In a fig. 5 the model of the gamma shield block (1:10), welded of 4 rings is shown. All technological operations were optimized during this manufacturing process.

Fig. 5. Model of the gamma shield block (1:10)

[1] BBGS - **B**lock of **B**iological **G**amma **S**hield
[2] AMG-6 – Aluminum alloy with ~6 wt % Mg

The results of the technological researches have shown a capability and expediency of combination of a casting uranium rings process with casing in a stainless steel shell (12Cr18Ni10Ti).

Jacket mould represents the welded construction consisting of a bottom and two coaxial shells, which are welded to it (all made of 12Cr18Ni10Ti stainless steel). Steel sheets are bended and subsequent argon-arc weld makes the shells.

The protective coating on a base of phosphate [2] is sprayed on the internal surface of the jacket mould for preventing of interaction of molten uranium alloy BZ-2 and stainless steel. Before coating the internal surfaces of the foundry form are treated by sandblasting to increase an adhesion between coating and stainless steel.

Melting and casting of uranium alloy BZ-2 are carried out in an industrial vacuum induction furnace equipped for obtaining of BBGS ring-type elements.

Uranium alloyed materials used for preparation of BZ-2 are selected of the waste and defective goods taking into account the content of alloyed elements and specification of BZ-2.

II.A.IV. Computational Substantiation of TPCS-117

The computational researches of TPCS-117 safety were carried out by RFNC-VNIIEF with use of a certificated complex of three-dimensional computational method including:
- Three-dimensional computational method C-95 (radiation and nuclear safety);
- Three-dimensional computational method AJAX-69 (thermal modes);
- Three-dimensional computational method DYNAMICS-3 (strength at dynamic loads);
- Three-dimensional computational method UPAKS (strength at quasistatic thermo-power effect).

The main results of computational researches of safety of TPCS-117 with 36 VVER-1000 SNFA are submitted below.

Radiating safety

Results of the researches carried out have shown that at normal operating conditions:
- On a TPCS surface radiation is 0.257 MeV/h (25.7 mBeR/h);
- On a distance of 2 m radiation is 0.072 MeV/h (7.2 mBeR/h).

At accidents:
- On a distance of 1 m radiation is 6.648 MeV/h (664.8 mBeR/h).

Thus, TPCS-117 is radiation safe at normal operating conditions and at accidents in accordance to national and IAEA requirements.

Nuclear safety

The calculations of TPCS-117 nuclear safety parameters were carried out for the most conservative terms.

Calculations show that:
- At normal operating conditions the value of $K_{eff} \leq 0.3$ that confirmed the deep sub-criticality of a system;
- At accidents $K_{eff} = 0.932$.

Thus, the TPCS-117 with 36 VVER-1000 SNFA meets the nuclear safety requirement ($K_{eff} < 0.95$).

Thermal modes

The computational substantiation of TPCS-117 thermal modes was carried out employing three-dimensional method for normal operating conditions, accidents and over-design situations.

At normal operating conditions when the container thermal condition is determined only by an internal heat source 40 kWt:
- Maximum temperature of the most heated fuel element does not exceed 260°C, that less then limit temperature 350°C;
- Maximum temperature of the leakproof gaskets does not exceed 65°C;
- Maximum temperature on a container external surface does not exceed the limit temperature 85°C.

Thus, TPCS-117 meets all thermal requirements at normal operating conditions.

At accidents the effect of open flame with parameters of T=800°C, duration 30 min was investigated.

The results of investigations are as follows:
- Maximum temperature of the most heated fuel element does not exceed 332°C that is less then maximum allowed short temperature 380°C;
- Maximum temperature of the internal leakproof cover gaskets is ~394°C that does not exceed the limit temperature 500°C;
- Maximum gamma shield temperature is ~587°C.

Thus, TPCS-117 meets all requirements at accidents (open flame).

For over-design situations the following initial events were investigated:
- Affect of an open flame with parameters of T=800°C, duration 60 min;
- Blocking up the container with building fragments and ground, accompanied by violation of a heat output from outside surface;
- Loss of coolant (helium).

The results of investigations are as follows:
- In open flame with parameters of T=800°C during 60 minutes the maximum temperature of the most heated fuel element does not exceed 365°C that is less then maximum allowed short temperature 380°C. Maximum temperature of the internal leakproof cover gaskets is

~ 492°C that does not exceed limit temperature 500°C. Maximum gamma shield temperature is ~465°C;
- In case of 24 hour's blocking up with building fragments accompanied by violation of a heat output from container outside surface the maximum temperature of the most heated fuel element does not exceed 262°C that is less then maximum allowed short temperature 380°C. Maximum temperature of the external leakproof cover gaskets is ~69°C that is insignificantly more than allowed temperature 65°C. Maximum temperature of the internal cover gaskets is ~91°C that is much less than allowed temperature 500°C. Maximum gamma shield temperature is ~185°C;
- In case of coolant loss the maximum temperature of the most heated fuel element is 377°C that does not exceed maximum allowed short temperature 380°C. Maximum temperature on external cover gaskets is ~63°C that does not exceed allowed temperature 65°C. Maximum temperature on internal cover gaskets is ~78°C that is much less allowed temperature 500°C. Maximum temperature of gamma shield is ~98°C.

Thus, TPCS-117 meets all thermal requirements at over-design situations.

Strength and leakproofness

The computational substantiation of TPCS-117 strength loaded with 36 VVER-1000 SNFA was carried out using three-dimensional method. The results of investigations are as follows:

At normal operating conditions:
- The design of the container at internal operating pressure P=15 atm is in accordance with strength standard;
- The design of the container at railway transportation is vibrationproof. The lowest personal oscillation frequency of a container is 65 Hz that is 1.6 times higher than the upper value of driving frequency at transportation. This property meets the requirement to personal frequencies of design;
- The strength body of container works in an elastic range and at effect of internal heat source of 40 kWt provides the thermo-stability of design. In open flame (T=800 °C, duration 60 min) strength body of container works behind the elastic limit. The minimum reserve for the limit strain equals 6;
- Strength and leakproofness of container design is provided at normal operating conditions.

At accidents:
- The TPCS-117 design at external hydrostatic pressure of 20 atm is in accordance with the strength standard;
- At drop from an altitude of 9 m and smash on a barrier the system of shock absorption used in a container design provides the acceleration not more than 10 g. The container design retains strength and leakproofness.

On a base of calculations carried out it is possible to conclude that at normal transport conditions and accidents the design of TPCS-117 intended for transportation and storage of 36 VVER-1000 SNFA retains the strength and leakproofness in accordance with national and IAEA requirements.

II.A.V. Estimation of TPCS-117 Stability at Terrorist Attack

As a result of calculations carried out it follows:
- At drop of the 120-t slab on TPCS-117 the container's body, covers and the members of their attachment are deformed elastically. Container retains the strength and leakproofness;
- At impact of an airplane (speed 100 m/s) into container its body in a zone of shock will be deformed elastic-plastically. Outside of a shock zone the body will be deformed elastically. Covers and the members of their attachment retain the strength;
- Armour-piercing fiery bullet (caliber 12.7 mm) does not make a hole in TPCS-117. The container retains leakproofness.
- Grenade of caliber 90 mm makes a hole in the body of container. However the radiation emergency is local. Range of the contaminated territory requiring the evictment and decontamination is ~3.8 km, and its square is ~0.69 km^2.
- At explosion of 50 kg explosive the container has a large plastic deformation, but it retains leakproofness.

II.B. Dual-Purpose TPCS for Transportation and Storage of SSE

Dual-purpose TPCS for transportation and storage of spent spark elements (SSE) of plutonium production uranium-graphite ADE type reactors consist of the shielding container and internal space for disposition of SSE (fig. 6).

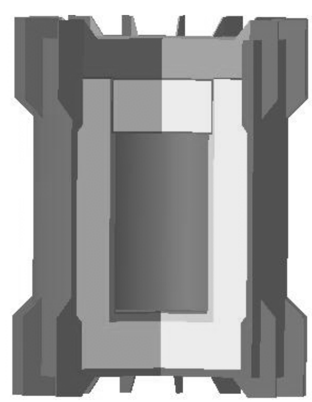


Fig.6. The design-layout scheme of dual-purpose TPCS for SSE transportation and storage

The development of this TPCS was stipulated the necessity to export the SSE accumulated stockpiles to enterprise "MAYAK" for reprocessing. Now there is no suitable container for SSE transportation. Using technical and technological decisions tested at development of TPCS-117 the preliminary design [5] of dual-purpose TPCS on a base of depleted uranium intended for transportation and disposal of SSE was made.

During the development we have taken into account the following:

- Average radioactivity of fission splinters after 10-year's endurance of SSE is 100 Curie/kg;
- Limit of radiation on a surface must not exceed 0.33 of natural background radiation;
- We need to use the present transport-technological schemes of SSE management;
- We need use available lifting tackles.

Two versions of a TPCS design were developed for loading of 120 SSE and 540 SSE.

Main parameters of TPCS for 120 SSE are:

- Mass of empty TPCS, not more than 2.2 t;
- Mass of loaded TPCS, not more than 2.25 t;
- External diameter - 560 mm.
- External size with shock absorbers - 660 mm.
- Height - 800 mm.
- Height with shock absorbers - 900 mm.
- Internal diameter - 320 mm.
- Height of internal space - 480 mm.

Main parameters of TPCS for 540 SSE are:

- Mass of empty TPCS, not more than 6.2 t;
- Mass of loaded TPCS, not more than 6.5 t;
- External diameter - 930 mm;
- External size with shock absorbers - 1030 mm;
- Height - 1360 mm;
- Height with shock absorbers - 1460 mm;
- Internal diameter - 690 mm;
- Height of internal space - 1035 mm.

Designs of dual-purpose containers provide a capability of transportation by railway, water transport and enable transportation by motor transport on especial trailers. The results of computational investigations confirm the design's meeting to national and IAEA safety requirements at normal operating conditions and accidents. TPCS retains stability at probable terrorist acts also.

III. COMPARISON WITH SIMILAR DESIGNS

The best foreign and domestic analogues were chosen for comparison with containers developed. The comparative data are shown in tables II and III.

TABLE II. Comparison of TPCS-117 with foreign analogues

Characteristics	Container developed	Analogue 1	Analogue 2
Mark	TPCS-117	NAC-STC	Castor V/21
Producer	Russia	«NAC Int.», USA	GNB, Germany
Height	6000 mm	4900 mm	4886 mm
External diameter	2700 mm	2515 mm	2400 mm
Gamma shield	Stainless steel, depleted uranium	Stainless steel, lead	Pig iron with spherical graphite
Neutron shield	Siloxane rubber	Resin	Polyethylene rods
Mass with load	144.5 t	116 t	106 t
Capacity, number of SNFA	36 SNFA VVER-1000 (~14 t U)	26 SNFA PWR or 57 SNFA BWR (~10 t U)	21 SNFA PWR (~8.4 t U)
Holding in pool, years	3 – 5	6.5	5.0
Heat output	40.0 kWt	22.1 kWt	20.0 kWt
Specific cost/1t U	57,000 USD	81,000 USD	59, 000 USD

TABLE III. Comparison of transport packing complete sets for SSE

Gamma shield	Capacity	Overall dimensions, mm	Mass	Specific mass
Pig iron	120 SSE	∅930, L=1360	8.5 t	70.8 kg/p.c.
Uranium	120 SSE	∅560, L=800	2.2 t	18.3 kg/p.c.
Uranium	540 SSE	∅930, L=1360	6.5 t	8.5 kg/p.c.

IV. CONCLUSIONS

The utilization of metallic depleted uranium has provided creation of dual-purpose transport packing complete sets with a maximum specific loading of spent nuclear fuel.

The dual-purpose transport packing complete sets with a depleted uranium gamma shield completely meet up-to-date national and IAEA safety requirements and provide defense against terrorist acts. The warranty service life of such containers exceeds 50 years.

The greatest effect of metallic uranium use is supposed to be attained with the design of small-sized TPCS.

ACKNOWLEDGMENTS

Authors sincerely thanks Peter Gavrilov - Chief engineer of Siberian Chemical Combine and Valery Fatin - Director of a reactor plant of the same Combine for activity and participation in discussion of results.

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